

## Improved Performance of Li-Ion Cells Under Pulsed Load Using Double-Layer Capacitors in a Hybrid Circuit Mode

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### Abstract

Electrical characteristics of hybrid power sources consisting of Li-ion cells and double-layer capacitors were studied at 25°C and -20°C. The cells were initially evaluated for pulse performance and then measured in hybrid modes of operation where they were coupled with the high-power capacitors. Cells manufactured by Panasonic measured at 25°C delivered full capacities of 0.76 Ah for pulses up to 3A and cells from A&T delivered full capacities of 0.73 Ah for pulses up to 4A. Measured cell resistances were 0.15 ohms and 0.12 ohms, respectively. These measurements were repeated at -20°C. Direct coupling of the cells and capacitors ("coupled hybrid") using 10F Panasonic capacitors in a 8F series/parallel combination extended the full capacity pulse limits (3.0V threshold) to 5.6A for the Panasonic cells and to 9A for the A&T cells. A similar arrangement using 100F capacitors from Elna in a 60F combination increased the Panasonic cell limit to 10 A. Operation in a "uncoupled hybrid" mode using uncoupled cell/capacitor discharge allowed full cell capacity usage at 25°C up to the capacitor discharge limit and showed a factor of 5 improvement in delivered capacity at -20°C.

### Introduction

Pulsed current applications of battery systems are becoming more demanding and more common. Communication systems using high-power bursts of digitized and compressed voice and data are of special interest to the military. These applications and other similar uses requiring intermittent high-power usage of present batteries can result in significant reduction of available battery capacity when fixed threshold voltage criteria are required for operation. The limitations of performance become even more severe at low temperature where cell impedance increases rapidly.<sup>1</sup>

High-power pulse capability can be achieved by combining the energy storage advantage of an electrochemical cell with the high-current capability of the new supercapacitors to form a hybrid power system. Only a few results are available for such hybrid power sources.<sup>2,3</sup> This paper reports on a hybrid power system combining Li-ion cells and double-layer capacitors to extend the current capabilities of the battery system and allow full usage of the electrochemical capacity. Although the capacitors used in this study were not optimized for minimal volume with respect to the Li-ion cells, they do allow determination of the improvement in cell performance that can be obtained as a function of electrical circuit parameters.

### Experimental

Commercially available Li-ion cells were obtained from two sources: Panasonic CGR17500 and A&T LSR17500. These cylindrical "AA" cells are rechargeable Li-ion cells using CoO<sub>2</sub>-based cathodes and intercalating carbon anodes. At full charge, the cell voltage is 4.1V and the cell capacities are approximately 0.72 Ah for the A&T cells and 0.76 Ah for the Panasonic cells. The cell resistances were initially characterized as a function of current and temperature using a spectrum impedance analyzer (PAR Model398).<sup>1</sup> At 25°C the Panasonic cells showed a net resistance of approximately 0.15 ohms while the A&T cells were about 0.12 ohms. The resistances were quite constant at temperatures above -10°C, but increased significantly at lower temperatures, limiting the current pulse amplitudes available from these cells.<sup>1</sup> The cells were stacked in series of three to yield a total stack voltage of 12.3V in the fully charged state. A computerized test apparatus was constructed to allow characterization of the individual cells and parallel cell/capacitor strings. The system also simulated "smart electronic" usage of the individual cell and capacitor components whereby the computer controls capacitor discharge rate, recharge current from the Li-ion cells and pulse frequency.

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Double-layer capacitors (18mm OD by 35mm) were obtained from Panasonic (AL series Gold) rated at 2.5V and 10F capacitance. Capacitors (35mm OD by 50mm) were also obtained from Elna (Dynacap DZ-2R5D107) rated at 2.5V and 100F capacitance. The manufacturers' reported resistance at 20°C for the Panasonic capacitors was 0.1 ohms (1kHz) while the Elna capacitors were rated at less than 0.08 ohms. The capacitors were combined in strings of five series-connected capacitors, four parallel strings for the Panasonic capacitors yielding an effective capacitance of 8F and a nominal effective resistance of 0.13 ohms while the Elna capacitors were configured in three parallel strings yielding an effective capacitance of 60F and a resistance of 0.13 ohms.

The experimental plan was to first characterize the pulse performance of the cell stack at room temperature using constant current pulses of 1-5s. The stack voltage and the individual cell voltages were monitored and the discharge program halted when the stack voltage dropped below 9V or any cell voltage dropped below 3V. These voltage limits were chosen to prevent any degradation of the  $\text{Li}_x\text{CoO}_2$  cathode material.<sup>4,5</sup> Cell resistances were determined from the measured voltage drop and current level during the individual pulses. The pulse repetition period was set at 40s to provide a constant comparison to the other hybrid discharge profiles. After each discharge run, the cells were recharged using an Arbin test system (Arbin Model BT2042), which allowed accurate determination of the cell capacity prior to each run. After this initial characterization, the cells were remeasured in a "coupled hybrid" mode where the cells were directly connected in parallel to the capacitors and discharged as a single unit, again using a 40s pulse repetition period. Finally, the hybrid system was operated in the "uncoupled hybrid" mode. The cells initially charged the capacitors to a 9V level corresponding to the minimum stack voltage so that the capacitors were always discharged starting at a fixed voltage for each pulse. Then the cells were removed from the capacitors and the capacitors discharged at the constant-current rate. This sequence was repeated until the cells or cell stack dropped below the voltage-threshold criteria. A selectable series resistor limited the current level from the cells during capacitor recharge. Consequently, this resistance determined the capacitor recharge time and thus the pulse repetition period of the discharges which was set for a minimum 40s period. This minimum period between pulses allowed for full cell recovery. The computer can be programmed to simulate any "smart" charge/discharge profile desired to determine the optimum usage of the individual cell/capacitor characteristics.

### Pulse Performance at 25 °C

#### *Direct Discharge Mode*

Direct pulse discharge of the cells using the Panasonic capacitors resulted in almost full cell capacities being realized up to current levels of about 3A for the Panasonic cells and about 4A for the A&T cells. Above this level, the usable cell capacities quickly dropped. Runs performed at pulse widths from 1s to 15s had no effect on the delivered capacity. The measured cell capacities for all discharge modes are shown in Figures 1 and 2 for the Panasonic and A&T cells, respectively. The open circuit voltage and the cell resistance determine the usable cell capacity at a given current for a fixed-voltage threshold. The discharge voltage profiles for the individual A&T cells during several sequential pulses are shown in Figure 3. The voltage profiles of the same individual cells and the cell stack over the entire discharge period are shown in Figure 4. The voltage drop during pulsing was used to calculate the resistance as shown in Figure 5. The cell resistances remained fairly constant over the cell discharge range until the very end of cell life when the cell resistances began to increase.

#### **Panasonic Capacitors**

#### *Coupled Hybrid Mode*

Pulsing the cells in the "coupled hybrid" mode resulted in extended delivered cell capacity for both cell types. Figures 1 and 2 show that the pulse current level for the Panasonic cells increased by about 50% (3.8A to 5.6A) while the A&T cells increased by about 100% (4.8A to 8.9A) using the 3.0V/cell threshold criteria.

The effective resistance,  $R_{\text{eff}}$ , of this cell/capacitor hybrid change as a function of time, initially showing capacitor-like characteristics and then behaving like the cell at longer times. The resistance can be expressed as:

$$R_{\text{eff}} = \frac{R_{\text{batt}} (R_{\text{cap}} + t/C)}{R_{\text{batt}} + R_{\text{cap}} + t/C} \quad (1)$$

Where  $R_{\text{batt}}$  is the resistance of the cell configuration,  $R_{\text{cap}}$  is the capacitor configuration resistance, and  $C$  is the total capacitance.

$$\text{At } t = 0: \quad R_{\text{eff}} = \frac{R_{\text{batt}} R_{\text{cap}}}{R_{\text{batt}} + R_{\text{cap}}} \quad (2)$$

$$\text{And at long times: } R_{\text{eff}} = R_{\text{batt}} \quad (3)$$

For the A&T cells, resistances of the individual cells and the cell/capacitor configuration were measured during the mid-discharge region and the effective single-cell resistances (1/3 of measured configuration resistances) at  $t=0$  were calculated as:

$$R_{\text{batt}} = 0.156 \text{ ohm} \quad R_{\text{cap}} = 0.049 \text{ ohm} \quad R_{\text{eff}} = 0.0373 \text{ ohm.}$$

Figure 6 shows the measured resistance during one pulse and the calculated single cell resistance. These results are in good agreement considering that the actual capacitance of the capacitor assembly was not measured but only calculated using nominal values for each capacitor.

### *Uncoupled Hybrid Mode*

Operation of the system in the "uncoupled hybrid" mode allows the cells to be used in their most efficient, low-current mode for capacitor charging while using the capacitors for the high-power pulses. Again looking in Figures 1 and 2 at the "uncoupled hybrid" data, cell capacities over 98% of original charge values were obtained. A selectable series resistor limited the cell currents during the charging period. Peak charging currents of up to 750 mA (1C rate) with an average charging current of 500 mA were typical during these runs as shown in Figure 7. Lower charging currents would result in even more efficiency, especially at lower temperatures.

### **Elna Capacitors**

#### *Coupled Hybrid Mode*

Measurements with the Elna capacitors allowed determination of system improvement for an increase in overall capacitance. These 100F/2.5V capacitors were combined in a series/parallel arrangement to give a 60F/12.5V effective system capacitance. The cell/capacitor hybrid was measured in the coupled mode up to the 10A limit of the power supply. Figure 8 shows a comparison of the A&T cell delivered capacity for the 10F and 100F component hybrids: The Elna capacitor hybrid sustained pulses up to 9A before showing a decrease in cell capacity while still providing over half of cell capacity at 10A. The associated single-cell effective resistances, shown in Figure 9, are significantly lower for the 100F component hybrid compared to the 10F Panasonic capacitors.

## Pulse Performance at -20 °C

### *Uncoupled Hybrid Mode*

At temperatures below -10°C, cell resistance increases rapidly, significantly limiting the available cell capacity.<sup>1</sup> More of the electrochemical capacity of the cell can be accessed if the cells are used in a low-current charging mode as employed by the "uncoupled hybrid" system. As a test of this system under these conditions, the Panasonic cells were cooled to -20°C and connected to the hybrid test system using the 8F Panasonic capacitor configuration. The capacitors remained at room temperature for these measurements to allow independent determination of improvement in cell performance for fixed circuit parameters. The cells were initially discharged by direct current pulses to determine deliverable capacity and then used to recharge the capacitors (uncoupled hybrid mode). Table I below lists the discharge conditions and shows that a factor of five improvement in capacity was obtained. Lower charging currents would result in even more efficient use of the cell capacities.

**Table I. Cell Performance in Direct and Hybrid Mode at -20°C**

	<b>Pulse(A)</b>	<b>Pulse(s)</b>	<b>Avg. Cell(A)</b>	<b>Capacity(Ahr)</b>
<b>Direct</b>	<b>0.53</b>	<b>4</b>		<b>0.024</b>
<b>Hybrid</b>	<b>4</b>	<b>4</b>	<b>0.34</b>	<b>0.129</b>

## Conclusions

A hybrid cell/capacitor tester was used to demonstrate extended performance of Li-ion batteries under pulsed-current conditions. Parallel coupling of the cells and capacitors resulted in a reduction of system resistance, allowing extended discharge periods for cells with fixed discharge voltage criteria.

Direct coupling of the cells and capacitors in a "coupled hybrid" mode resulted in a 50%-100% improvement of delivered capacity at room temperature. Using a computer controlled tester to simulate smart control electronics, the full capacity of the cells was obtainable to recharge the capacitors for high-current pulses. The output current pulses obtained were determined strictly by the properties and number of the capacitors used. Use of the "uncoupled hybrid" system resulted in a factor of five improvement in available cell capacity at -20°C where high cell resistance severely limits performance. Even higher efficiencies are obtainable for applications with lower charge currents and longer charge times. Practical application of hybrid systems would require significant reduction of capacitor volume for a given voltage/capacitance value or improvement in the voltage stability range which would allow fewer components for a given voltage requirement. The use of "smart control" electronics would allow the most efficient use of the cell and capacitor components over a wider range of temperatures.

## Acknowledgements

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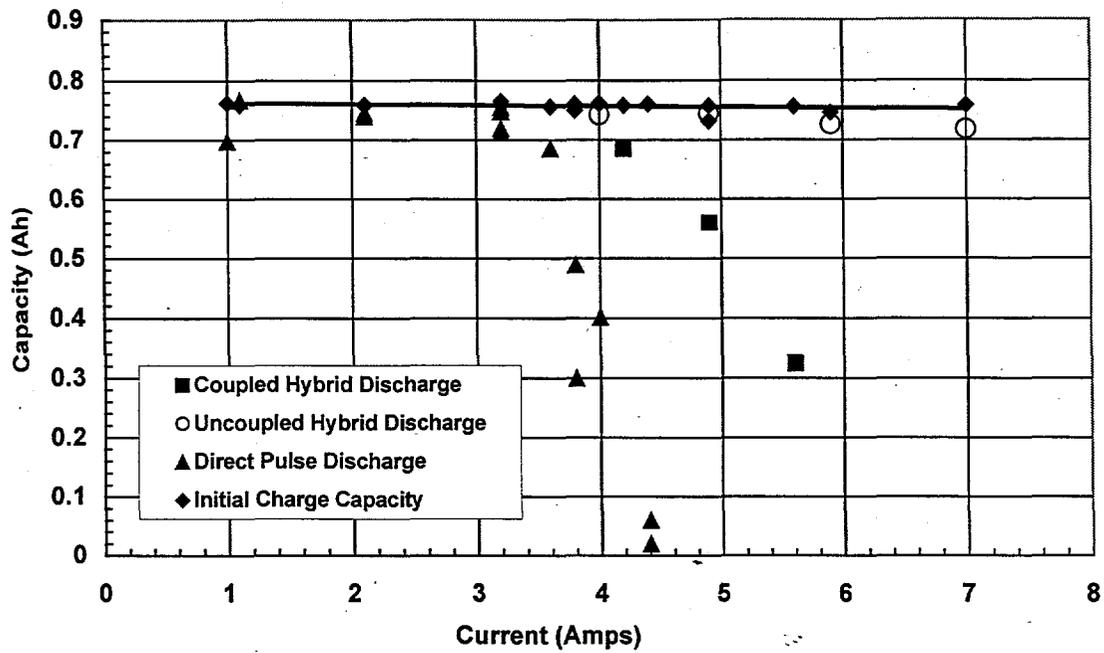


Figure 1. Delivered capacity of Panasonic Cells under direct and coupled/uncoupled hybrid pulse conditions (25C).

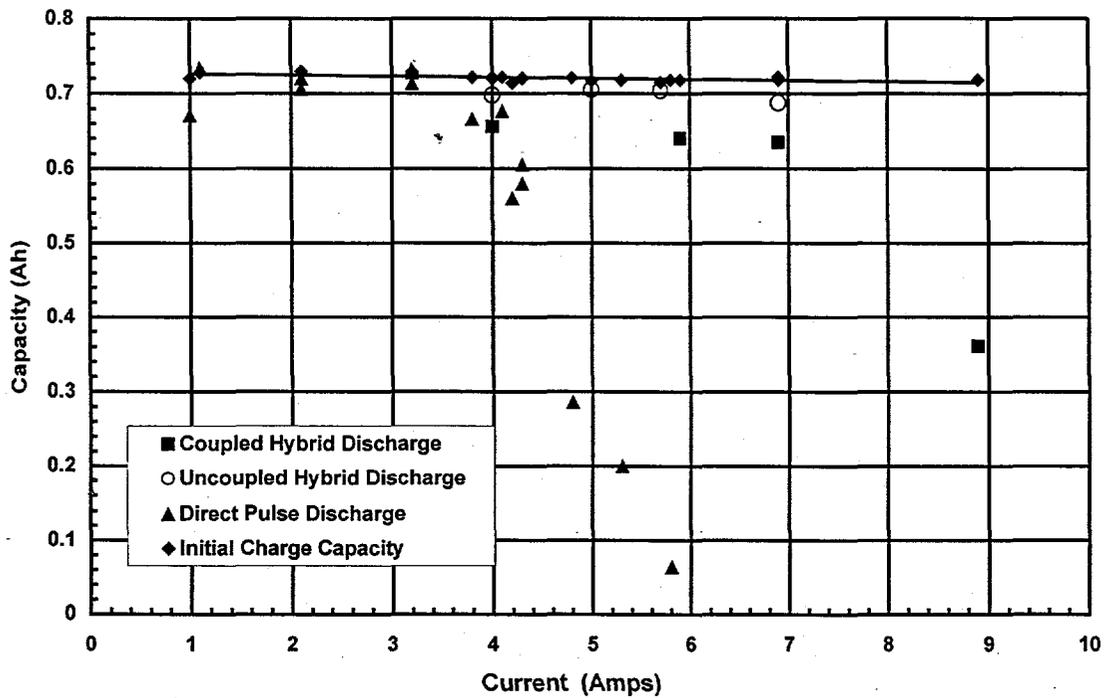


Figure 2. Delivered capacity of A&T Cells under direct and coupled/uncoupled hybrid pulse conditions (25C).

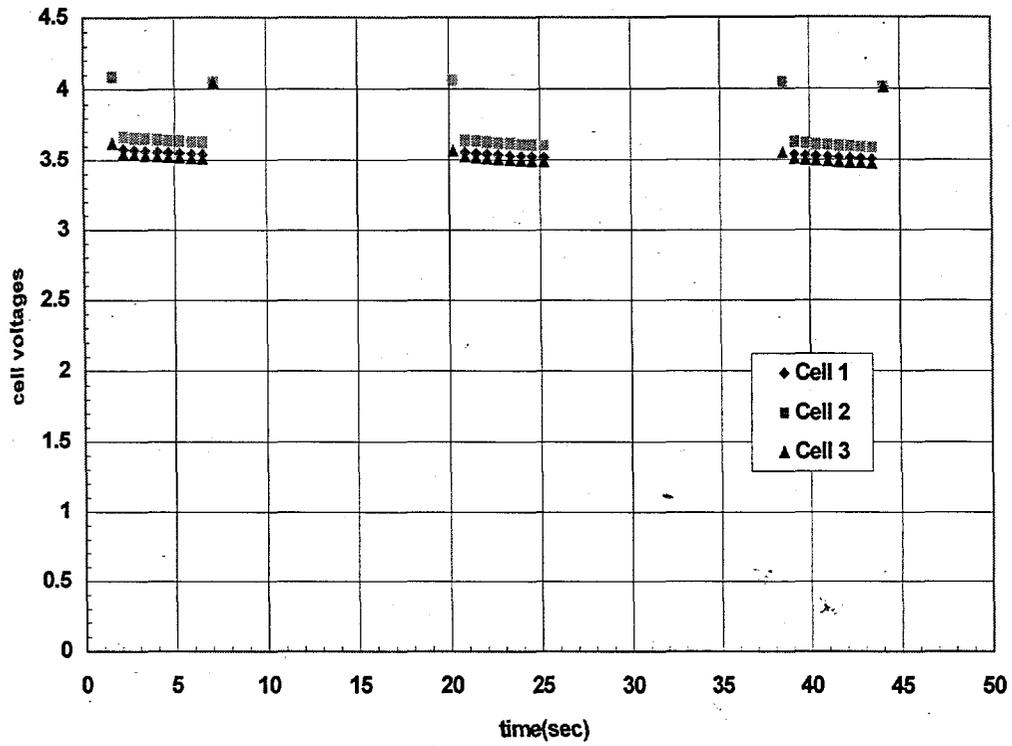


Figure 3. Direct pulse discharge voltage profiles of A&T cells for 3A, 5s output pulses (25C).

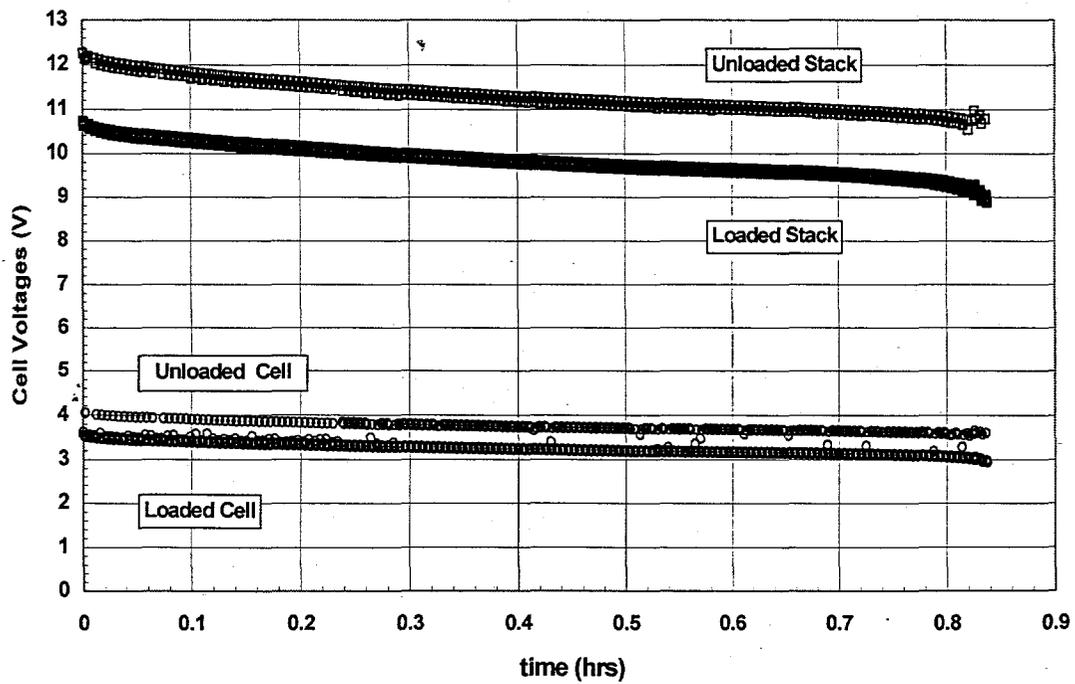


Figure 4. Direct pulse discharge voltage profiles of A&T cells and the cell stack for 3A, 5s output pulses (25C).

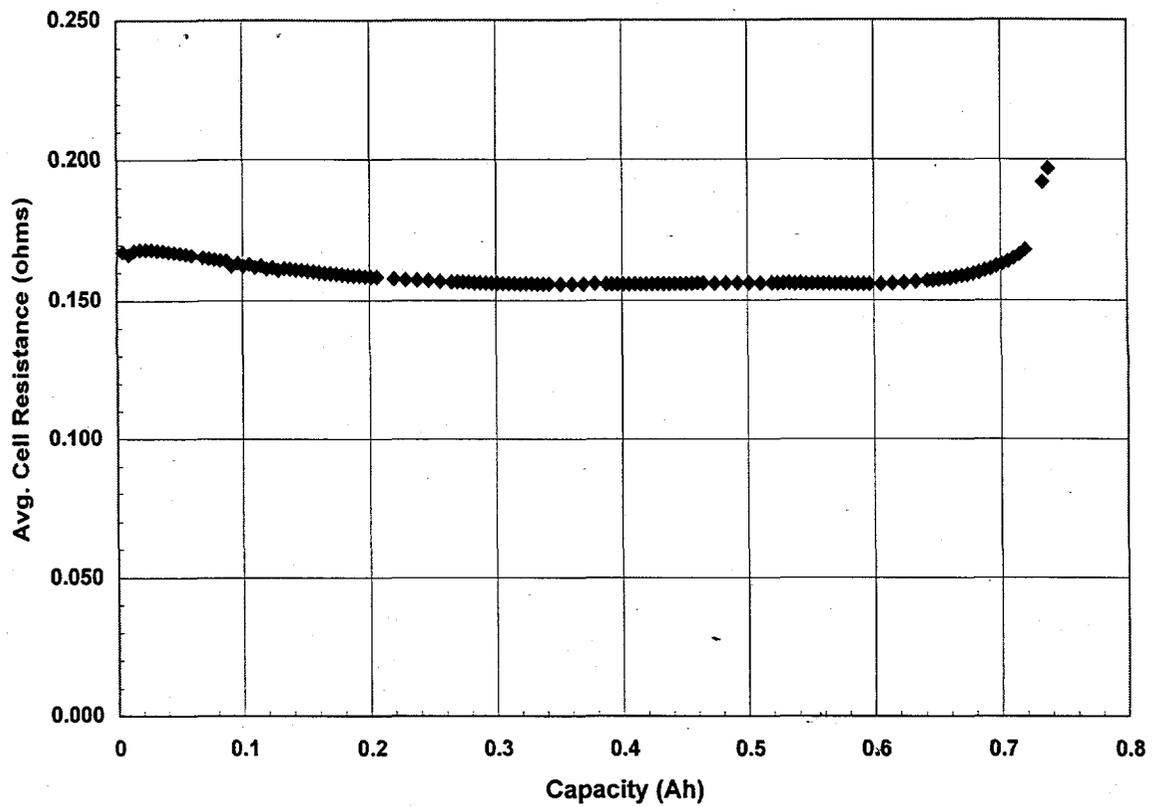


Figure 5. Measured cell resistance during direct pulsing of A&T cells for 3A, 5s output pulses (25C).

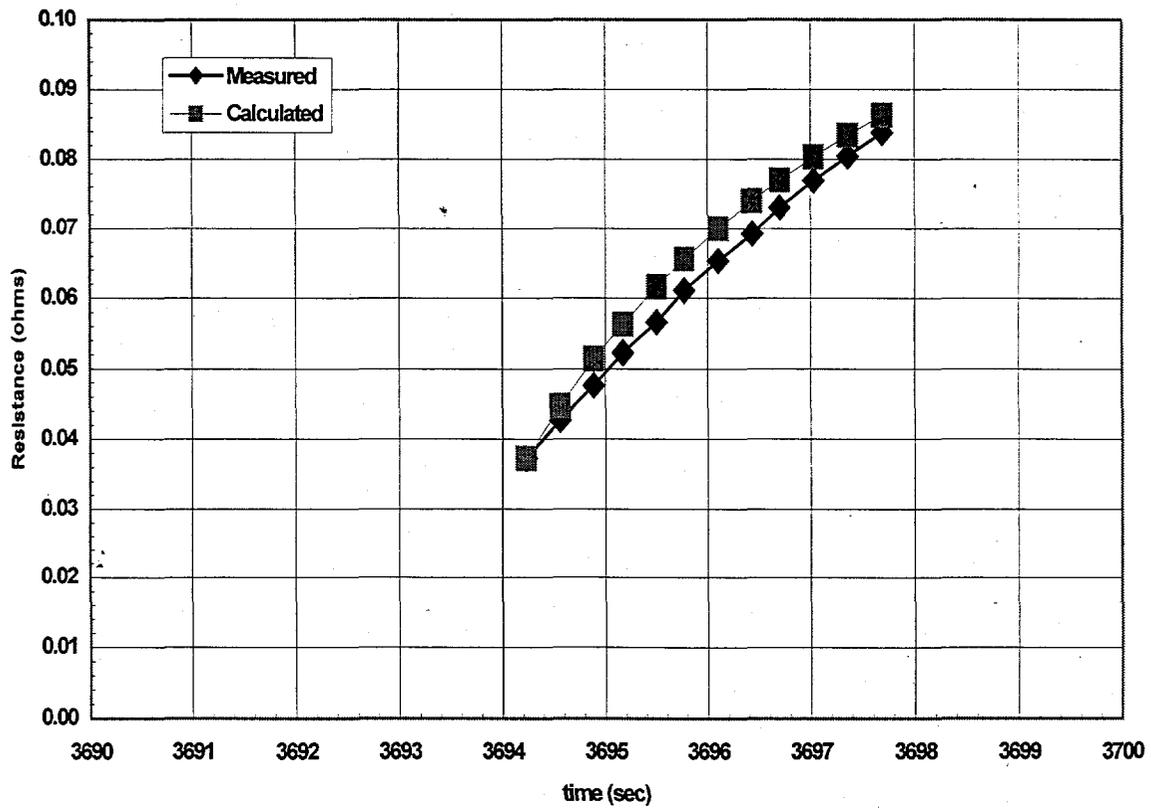


Figure 6. Measured single-cell effective resistance of 8F "coupled hybrid" system using A&T cells for 4A, 4s output pulses and the calculated resistance values (25C).

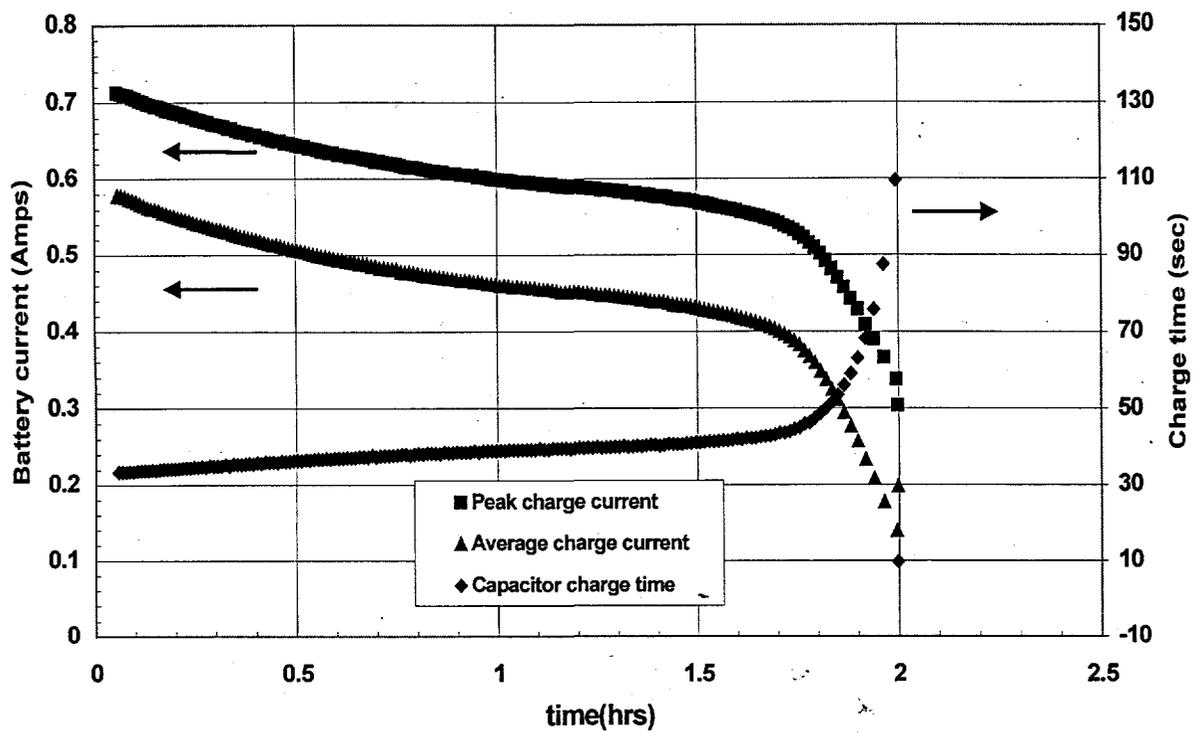


Figure 7. Peak and average charging currents with associated charging time during capacitor recharge for “uncoupled hybrid” system for 7A, 2s output pulses (25C).

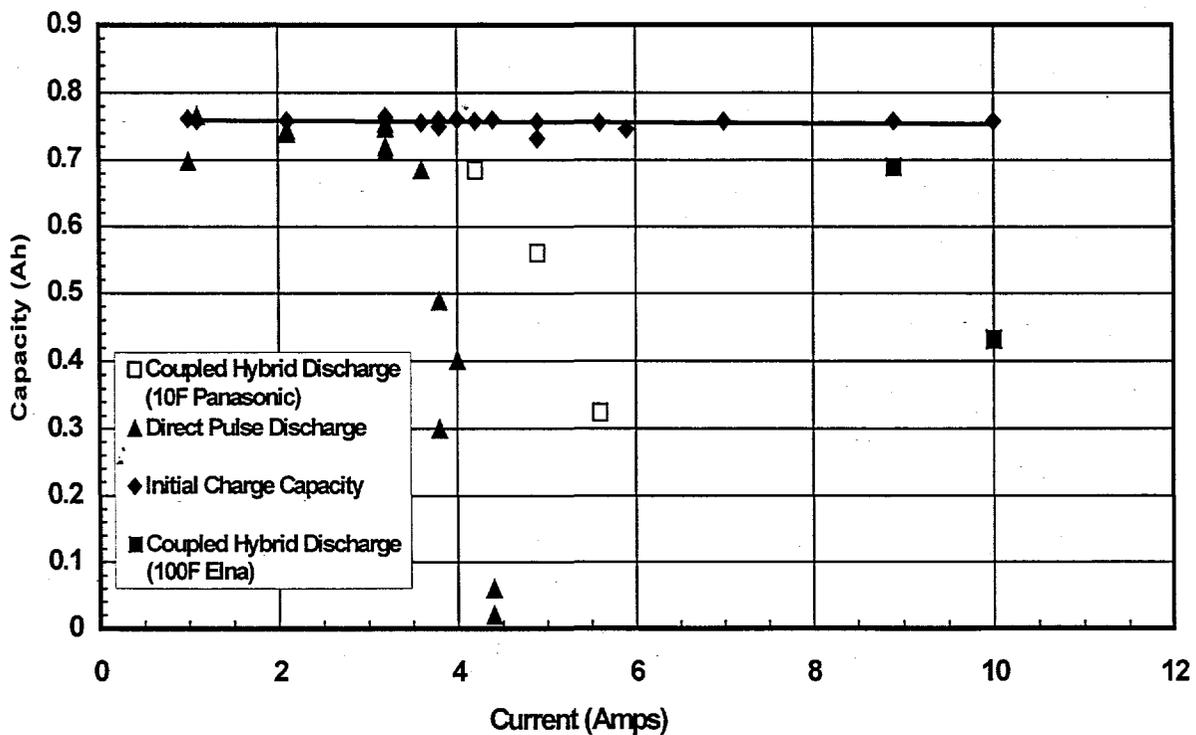


Figure 8. Delivered capacity of Panasonic cells under direct and “coupled hybrid” pulse conditions (25C) with 10F Panasonic capacitors and 100F Elna capacitors.

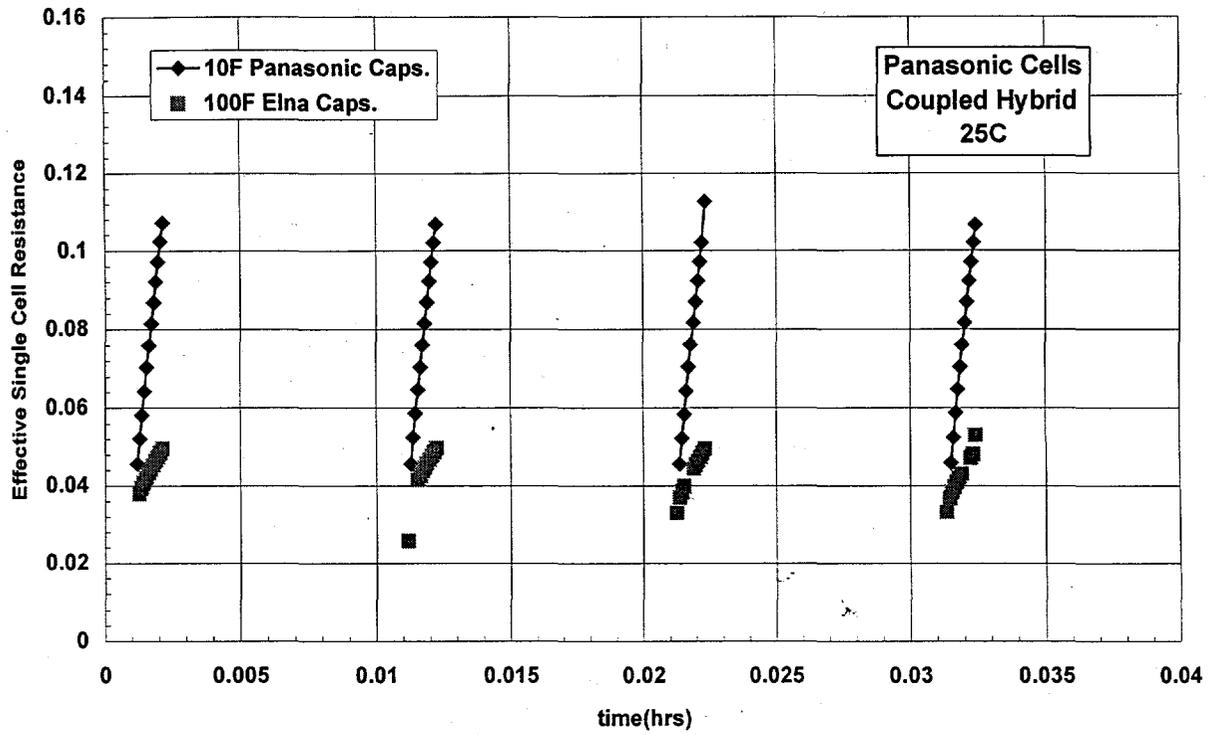


Figure 9. Effective single-cell resistance for Panasonic cells in “coupled hybrid” mode with 10F Panasonic and 100F Elna capacitors.